

How tropical instability waves impact the equatorial Pacific interannual SST variability and heat budget in 2024

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Abstract

Tropical instability waves (TIWs) are mesoscale waves in the Pacific cold tongue that induce sea surface temperature (SST) perturbations, playing a significant role in modulating the El Niño-Southern Oscillation (ENSO). Observation and model simulations indicate that strong TIW activity occurred during the 2023/24 El Niño decaying phase (July–August). However, it remained unclear how TIWs influenced the spatiotemporal evolution of SST and to what extent they contributed to the suppressed development of the anticipated La Niña in 2024. In this study, we use an ocean general circulation model (OGCM) to quantify the contribution of TIWs to equatorial heat transport and their feedback on ENSO by comparing two simulations with and without TIWs. Results show that the 2024 TIWs acted as an important factor suppressing the transition to a La Niña event, weakening cold SST anomalies in the Niño3 region by 49%. A heat budget analysis further reveals that TIW-induced advection promoted warming of the cold tongue by up to $0.81^{\circ}\text{C month}^{-1}$, around 2.8 times larger than the net heat flux. These findings offer critical insights into the physical mechanisms governing TIW–climate interactions and provide a valuable foundation for improving ENSO prediction, particularly in accounting for the suppressed La Niña development in 2024.

Introduction

Tropical instability waves (TIWs) are prominent intraseasonal mesoscale phenomena observed in the equatorial Pacific and Atlantic Oceans (Düing et al. 1975; Legeckis 1977; Philander 1978). In the Pacific, TIWs typically appear as cusp-like, westward-propagating fluctuations of the sea surface temperature (SST) front north of the equatorial cold tongue. These waves are characterized by wavelengths of 1,000–2,000 km, phase speeds of around 0.4–0.6 m/s, periods of 20–40 days, and associated SST perturbations of up to $1\text{--}2^{\circ}\text{C}$ (Qiao and Weisberg 1995; Chelton et al. 2000; Lyman et al. 2007; Zhang 2014). The energy of TIWs is primarily generated by barotropic instability from the meridional shears within the equatorial current system (Philander 1976; Qiao and Weisberg 1998) and baroclinic instability driven by the meridional SST gradient over the cold tongue front (Cox 1980; Masina et al. 1999). Both instability mechanisms are closely related to the thermodynamic structure of the tropical Pacific cold tongue (Yu and Liu 2003). Therefore, quantifying the TIW-induced heat transport is crucial for understanding how these waves modulate the mean state and climate variability.

As an important component of the tropical Pacific climate system, TIWs play essential roles in ocean thermodynamic structure and marine ecosystems. Previous studies have shown that TIWs significantly contribute to the heat and momentum budgets of the cold tongue by modulating nonlinear heat fluxes and dynamical heating (Kessler et al. 1998, 2003; Xue et al. 2020; Whitt et al. 2022). In particular, they induce equatorward heat advection that effectively counteracts the cooling effect of equatorial upwelling in the cold tongue (Baturin and Niiler 1997; Kennan and Flament 2000; Menkes et al. 2006). For instance, Menkes et al. (2006) estimated that TIW-induced horizontal advection in an ocean general circulation model contributes a warming of $0.84^{\circ}\text{C month}^{-1}$, which is comparable to atmospheric heat fluxes. This heating effect has been consistently supported by subsequent observational and modeling studies (e.g.,

Jochum et al. 2007; Imada and Kimoto 2012). Beyond their physical impacts, TIWs modulate advection to influence nutrient supply and biological productivity (Chavez et al. 1999; Gorgues et al. 2005; Shi and Wang 2021; Eddebbar et al. 2024), which in turn can feed back to the upper-ocean thermal structure (Tian et al. 2018; Zhang et al. 2024).

Furthermore, TIWs modulate the mean state and variability of the tropical Pacific through two-way interactions with multiscale climate variability. At the seasonal scale, TIW activity intensifies from boreal summer to winter and weakens in the following spring, in phase with the cold tongue's seasonal cycle (Hansen and Paul 1984; Im et al. 2012; Xiong et al. 2026). This intensification is driven by prevailing trade winds that strengthen equatorial upwelling and zonal currents, resulting in a stronger meridional SST gradient and triggering both frontal and shear instabilities (Contreras 2002; Wang et al. 2017, 2019). At the interannual scale, TIWs are influenced by El Niño-Southern Oscillation (ENSO), the dominant mode of climate variability in this region. They are suppressed during El Niño due to a weakened meridional SST gradient and current shear but dramatically enhanced during La Niña (Hashizume et al. 2001; Yu and Liu 2003; An 2008). In turn, TIWs exert an asymmetric negative feedback on ENSO via nonlinear dynamical heating, warming the cold tongue more during La Niña than cooling it during El Niño, which partially contributes to ENSO amplitude asymmetry (Bryden and Brady 1989; An and Jin 2004; Imada and Kimoto 2012; Xue et al. 2020). Specifically, weakened TIW activity during El Niño reduces anomalous heat advection, limiting cold tongue warming and slowing El Niño growth; by contrast, intensified TIW activity during La Niña transports off-equatorial warm waters equatorward, weakening the cold tongue and dampening further La Niña development (Vialard et al. 2001; Xue et al. 2021; Wang et al. 2024). Additionally, TIWs can regulate ENSO phase transitions by modulating horizontal advection and the associated surface wind feedback (Nagura et al. 2008; Zhang 2016).

Numerical models are essential for quantifying TIW-induced processes and elucidating their multi-scale interactions with ENSO and the background climate state. Eddy-resolving models can realistically reproduce the spatiotemporal characteristics of TIW activity, whereas coarse-resolution models struggle to resolve these features, making it difficult to accurately quantify TIW-induced heat transport and feedback (Roberts et al. 2004, 2009; Imada and Kimoto 2012; Graham 2014). Using high-resolution simulations combined with sensitivity experiments, Maillard et al. (2022a, b) isolated the direct and rectified effects of TIWs on the seasonal cycle in the eastern equatorial Pacific. However, most previous studies have focused on the climatological mean state or typical ENSO phases, while the role of strong TIWs during ENSO transitions remains poorly understood and insufficiently quantified.

Previous analyses have demonstrated the TIW-induced warming effect on the equatorial cold tongue (Fig. S1) and revealed an asymmetric negative feedback on ENSO (Fig. S2), using an ocean general circulation model (OGCM) for 2009–2024. Notably, anomalously intense TIW activity appeared in boreal summer 2024 following the strong 2023/24 El Niño, yet the La Niña anticipated for late 2024 did not fully materialize (Tan et al. 2025; Shen and Zheng 2026). This raises a key question: whether the strong TIWs suppressed the expected La Niña by warming the cold tongue. Here, we use an OGCM to quantify TIW impacts on equatorial Pacific SST variability and ENSO transitions. The paper is organized as follows.

Section “Data and methods” describes the model configuration, experimental design, and heat budget methodology. Section “Results” evaluates the impacts of the 2024 TIWs on the interannual SST, and further quantifies their contribution to the heat budget. Finally, conclusions and discussion are presented in Section “Conclusions and discussion”.

Data and methods

An ocean general circulation model (OGCM)

The OGCM used in this study is the reduced gravity, primitive equation, sigma-coordinate model developed by Gent and Cane (1989) specifically for the upper equatorial ocean. Vertically, this model consists of a mixed layer (the first layer) and several layers below, which are separated based on a sigma coordinate (i.e., layer OGCM). Notably, the OGCM has been significantly advanced through a series of related studies (Murtugudde and Busalacchi 1998; Zhang et al. 2006). The main improvements include two key components: the embedding of a hybrid bulk mixed layer (ML) model to simulate upper-ocean vertical turbulent mixing (Kraus and Turner 1967; Price et al. 1986; Chen et al. 1994) and the coupling of an advective atmospheric mixed layer (AML) model to estimate sea surface heat fluxes (Siegel et al. 1995; Murtugudde et al. 1996).

The model domain spans the tropical Pacific (25°S – 25°N , 120°E – 76°W), with a zonal resolution of 0.33° and a meridional resolution from 0.23° to 0.72° , and with 25 vertical layers. Sponge layers are set near the northern and southern boundaries. The OGCM is initialized from the World Ocean Atlas (WOA) temperature and salinity fields (Levitus et al. 2005) and spun up for 100 years using atmospheric climatological forcing fields from NCEP/NCAR (Kalnay et al. 1996). In addition, a Newtonian relaxation scheme is applied to constrain the simulated SST to reduce systematic biases and ensure a realistic representation of the ocean state. These configurations effectively capture TIW signals (Zhang 2014, 2016).

Experimental design

To isolate the effects of the TIWs on the equatorial Pacific Ocean state, we perform two experiments using the OGCM. Both simulations are integrated for 16 years (2009–2024) after a long-term spin-up run in Section 2.1, forced by daily mean wind stress fields prescribed from the ECMWF Reanalysis version 5 (ERA5; Hersbach et al. 2020). The control simulation (CTRL), which retains all dynamical processes, allows TIW signals to develop and propagate naturally. The sensitivity simulation (FILT) employs the same configuration as the CTRL, but TIW-induced advective perturbations are filtered out each day by applying a 12° zonal low-pass filter (Tian et al. 2018, 2019), thereby excluding TIW effects. By comparing the daily outputs of CTRL and FILT runs, it is possible to isolate and quantify the distinct impact of TIWs on the ocean state.

Heat budget methodology

To quantify the role of TIWs in the heat budget of the equatorial cold tongue, we need to first separate the large-scale background fields and TIW perturbations from the original signals. Since TIW signals have obvious space characteristics (Chelton et al. 2001; Xie 2004), a spatial high-pass filter of 12° zonal moving average is applied to extract TIW-scale signals in this study (Hashizume et al. 2001). Therefore, each variable X can be decomposed into a slow-varying background state (overbar) and a TIW component (prime):

$$X = \bar{X} + X' \quad (1)$$

Furthermore, the mixed layer heat budget equation can be expressed as follows (Gent and Cane 1989):

$$\frac{\partial T}{\partial t} = -\left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y}\right) - w \frac{\partial T}{\partial z} + \frac{2\kappa}{H_m H_2} (T_e - T) + \frac{Q}{\rho C_p H_m} + R \quad (2)$$

where T and T_e are the temperatures in the ocean mixed layer and the subsurface layer, respectively; (u, v, w) are the zonal, meridional, and vertical velocities; κ is the vertical diffusivity coefficient; H_m and H_2 are the mixed layer depth and subsurface layer depth; Q is the net air-sea heat flux; ρ is the seawater density; and C_p is the specific heat capacity. The first term on the right-hand side represents the horizontal advection ($Hadv$), the second term denotes vertical advection ($Vadv$), the third term is the vertical mixing and entrainment, the fourth term represents the net heat flux (Q), and the last is the residual term.

Each of the above heat budget terms (Eq. (2)) is computed online by the OGCM and stored as a daily average. Moreover, the closure of the mixed layer budget equation was verified for the 2009–2024 simulation period. The sum of the advection, mixing, entrainment, and atmospheric heat flux terms closely balances the temperature tendency, with a negligible residual.

Based on this decomposition (Eq. (1)), each of the advective terms can be separated into four terms. For example, the zonal advection becomes

$$-u \frac{\partial T}{\partial x} = -(\bar{u} + u') \frac{\partial(\bar{T} + T')}{\partial x} = -\bar{u} \frac{\partial \bar{T}}{\partial x} - \bar{u} \frac{\partial T'}{\partial x} - u' \frac{\partial \bar{T}}{\partial x} - u' \frac{\partial T'}{\partial x} \quad (3)$$

where overbars and primes represent background mean variables and TIW perturbations, respectively. That is, the total advection term has been split into mean and perturbation components. Additionally, both the model and the observations have confirmed that cross terms become negligible in the long-term budget and are thus excluded from further analysis.

Results

Characteristics of TIW activity in 2024

To evaluate the ability of the OGCM model to reproduce TIW variability, we compare the simulated and observed spatiotemporal characteristics of root mean square (RMS) for TIW-induced SST perturbations (SST_{TIW}), which is represented by TIW intensity (Fig. 1 and Fig. S3; Yu and Liu 2003). The spatial patterns of TIW intensity from model simulation (Fig. 1b) are in good agreement with those from satellite observations (NOAA OISST, Reynolds et al. 2007; Fig. 1a). Both revealed strong TIW activity along the equatorial Pacific cold tongue (2°S – 6°N , 160° – 90°W) during the decay phase of the strong 2023/24 El Niño event (i.e., July–August 2024). The TIW intensity exceeds 0.5°C over 48% and 54% of the TIW active region in observations and simulation (green rectangles in Figs. 1a and b), respectively. Specifically, the larger amplitude of observed SST_{TIW} regions is in the north of the equatorial central-eastern Pacific ($\text{RMS} > 0.8^{\circ}\text{C}$), while the simulation in the CTRL run slightly underestimated it. This may be due to the fact that the OGCM used here has a marginal horizontal resolution, which limits the full representation of TIW amplitude (Zhang 2014).

The simulated seasonal cycle and interannual variability of TIW intensity are also similar to those observed over the TIW active region (Fig. 1c–e). As shown in Figs. 1c and d, TIW activity in 2024 was significantly stronger than the 2009–2024 climatology from May, reaching a peak intensity of $\sim 0.6^{\circ}\text{C}$ in boreal summer (July–August). Although the amplitude of TIWs in the model is slightly weaker than the observations, it captures well the phasing of its variability. From a long-term perspective, the 2024 TIW intensity ranks among the strongest during the past 16 years, surpassed only by those of 2010 and 2016 (Fig. 1e). This result shows that the intensity of SST_{TIW} exhibits remarkable interannual variability, which has been confirmed to be modulated by ENSO (Boucharel and Jin 2020). For example, TIW activity was suppressed in the 2015 El Niño phase, whereas the intensified TIW signal was observed during the subsequent 2016 La Niña event. Moreover, the time series of the simulated TIW intensity are consistent with observations, with a high correlation coefficient of 0.82 ($p < 0.01$).

Overall, the OGCM captures well the spatial and temporal variability of observed SST_{TIW} . It suggests that we can use the model to isolate and quantify TIW impacts on interannual SST and the aborted transition to La Niña in 2024.

Impact of TIWs on interannual SSTA and La Niña development

To investigate the 2024 TIWs impact on interannual variability, the differences in simulated SST anomaly (SSTA) fields between the CTRL and FILT experiments are shown in Fig. 2. In July–August, the spatial structure of SSTA in the CTRL run (Fig. 2a) is similar to that in the FILT run (Fig. 2b), exhibiting a broad band of negative SSTA along the equatorial cold tongue but with a striking difference in cooling amplitude. In the CTRL simulation, the inclusion of the TIW effect leads to a weakened cold tongue, with

negative SSTA ranging from -0.7°C to -0.2°C (Fig. 2a). By contrast, the FILT simulation displays notably stronger SST cooling, with a peak value of -1.2°C in the equatorial central and eastern Pacific (Fig. 2b). In particular, the spatially averaged SSTA over the Niño3 region (5°S – 5°N , 150° – 90°W) is -0.31°C in CTRL, but the cooling intensifies to -0.60°C in FILT, indicating that TIW activity damps the amplitude of SST cooling by 49%.

The direct impact of TIWs is more clearly revealed by the SSTA difference between the two experiments (CTRL – FILT) presented in Fig. 2c. It is found that a distinct band of strong positive heating anomalies extends across the Niño3 region, with amplitude reaching 0.3°C to 1°C . The TIW-induced major patterns of warming are concentrated in the 1°S – 4°N band along the equator ($> 0.8^{\circ}\text{C}$), while weak cooling anomalies appear in the surrounding regions, thereby reducing the meridional temperature gradient (Fig. S4). This spatial pattern indicates that TIWs play a critical role in redistributing thermal energy in the equatorial Pacific.

The modulation of SST anomalies by TIWs also exhibits pronounced seasonal variability (Fig. 2d). The time series of Niño3 SST anomalies, a key index of ENSO, reveals that both CTRL and FILT simulations reflect the significant cooling trend ($p < 0.01$) during the first half of 2024, but obvious divergences emerge starting in late boreal spring. The differences, indicated in green bars, clearly show that TIWs exert a persistent warming effect throughout the year, reaching a peak at about 0.3°C in summer (July–August), when TIW activity is most vigorous. This effect on SST changes is consistent with the seasonality of TIW variability (Figs. 1c and d). Furthermore, the seasonal cycle of Niño3 SSTA reveals the cumulative effect of TIW activity: a slight warming is seen in the non-active spring, intensifies during summer and autumn, and stays until winter, which corresponds to the results of Maillard et al. (2022b). This suggests that such time-integrated warming induced by TIWs effectively counteracts the background cooling tendency ($\text{SSTA} < -0.5^{\circ}\text{C}$ in FILT during June–October), which would favor the development of a La Niña event.

To summarize, taking into account the TIW effects (i.e., the CTRL run) causes a strong increase in SST in the cold tongue. These results demonstrate that the anomalous TIW activity acts as a critical dynamic factor in suppressing the transition to a La Niña phase in 2024. We further explore the underlying physical mechanisms responsible for this TIW-induced warming via a heat budget analysis in the next section.

Contribution of TIWs to the heat budget in the cold tongue

To further quantify the contributions of strong 2024 TIWs to SST in the cold tongue, we employ a mixed layer heat budget analysis of SSTA based on the OGCM simulation. Figure 3 shows the spatial distributions of the estimated SSTA budget terms during July–August 2024. The SSTA tendency displays a distinct meridional oscillation structure in the equatorial Pacific cold tongue, with alternating warm and cold fluctuations that reflect typical TIW signals (Fig. 3a). The tendency is mainly driven by the total heat advection term (Fig. 3b), while net surface heat flux is relatively small (Fig. 3c). In particular, the total

advection leads to an extreme warming band along the equatorial cold tongue, with heating rates exceeding $1.6^{\circ}\text{C month}^{-1}$ across the $160^{\circ}\text{--}100^{\circ}\text{W}$ region. The dominant contribution term, advection, is further decomposed into its horizontal and vertical components (Figs. 3d and g). The spatial pattern of horizontal advection (Fig. 3d) closely resembles that of total advection (Fig. 3b), indicating its primary role in the SST warming effect. In contrast, vertical advection causes a slight and almost negligible cooling effect on the temperature of the corresponding region (Fig. 3g).

Furthermore, the horizontal and vertical advectons are separated into background mean and fluctuating parts to isolate the specific role of TIWs. Comparing these components, it is clear that horizontal advection is mostly dominated by the TIW-induced fluctuating term (Fig. 3f), with only a minor contribution from its background component (Fig. 3e). The TIW-induced horizontal advection (Fig. 3f) exhibits a consistent pattern with both total advection (Fig. 3b) and TIW intensity (Figs. 1a and b), where the strongest heating center is concentrated in the central-eastern Pacific cold tongue (Fig. 2c). More concretely, the contributions of their zonal and meridional components to SST warming have a heterogeneous distribution across the equatorial Pacific (Fig. S5). The zonal advection component is found to be the primary contributor to the off-equatorial warming (around $1^{\circ}\text{--}4^{\circ}\text{N}$), with amplitudes exceeding $2^{\circ}\text{C month}^{-1}$ (Fig. S5c). Meanwhile, meridional advection dominates at the equator ($> 1.2^{\circ}\text{C month}^{-1}$), which contributes more than the zonal component (Fig. S5f). These findings demonstrate that the TIW-induced warming of the mixed layer is predominantly driven by the nonlinear interactions between velocity and temperature fluctuations (i.e., fluctuating horizontal terms), rather than by the advection associated with mean background gradients. However, the decomposition of vertical advection shows that neither the background nor the TIW-induced fluctuating component contributes significantly to the heat budget within the mixed layer (Figs. 3h and i), with magnitudes an order smaller than those of the horizontal terms. This is because weak vertical velocities and temperature gradients at the mixed layer bottom suppress vertical heat transport, consistent with previous studies indicating that TIW-induced vertical advection is negligible for the mixed-layer budget but critical for thermocline redistribution (Menkes et al. 2006; Maillard et al. 2022a).

Since the advection term is a key factor in the heat budget, its individual components warrant a more detailed quantitative analysis over the TIW-active cold tongue region ($2^{\circ}\text{S--}6^{\circ}\text{N}$, $160^{\circ}\text{--}90^{\circ}\text{W}$). Figure 4 illustrates good agreement between the OGCM-simulated advection contributions to the heat budget and those derived from the Copernicus Marine Environment Monitoring Service (CMEMS) reanalysis (Jean-Michel et al. 2021). The model effectively captures the dominant role of total advection in driving the cold tongue warming, contributing $0.88^{\circ}\text{C month}^{-1}$ during July–August 2024. Note that this substantial heating effect is almost entirely explained by the TIW-induced advection component ($0.81^{\circ}\text{C month}^{-1}$), which is much larger than the contribution from the background mean flow ($0.08^{\circ}\text{C month}^{-1}$). In addition, the TIW-induced warming is approximately 2.8 times larger than the net heat flux ($0.29^{\circ}\text{C month}^{-1}$), confirming that the 2024 SST anomaly was driven principally by lateral eddy dynamics rather than by air-sea interactions. Consistent with the aforementioned spatial distributions, the net TIW-

induced warming of the cold tongue is dominated by horizontal advection ($0.85^{\circ}\text{C month}^{-1}$), which obviously outweighs the weak cooling effect of vertical advection ($-0.04^{\circ}\text{C month}^{-1}$).

In summary, total advection, driven primarily by TIW-induced anomalous velocities and temperatures, is responsible for a first-order heating contribution to the SST budget in the equatorial Pacific. It is noteworthy that this warming is predominantly attributed to fluctuating horizontal advection, which acts to transport warm water to the equatorial cold tongue. Therefore, the 2024 TIWs led to a net warming of $0.81^{\circ}\text{C month}^{-1}$, damping the regional cooling tendency and providing the dynamic mechanism for the suppressed La Niña event discussed in the previous section.

Conclusions and discussion

In this study, we provide an assessment of the characteristics of the extreme TIW activity observed in 2024 and its impacts on the equatorial Pacific heat budget, with a focus on its role in interannual SST variability and the potential La Niña transition, using an OGCM. Two experiments are performed: a control run (CTRL) with TIW effects and a sensitivity run (FILT) without them via a zonal low-pass filter.

The results show that the OGCM can accurately reproduce the observed spatiotemporal variability of SST_{TIW} , with strong TIW activity ($\text{RMS} > 0.5^{\circ}\text{C}$) in the cold tongue during the 2023/24 strong El Niño decaying phase (July–August; Fig. 1). By comparing the CTRL and FILT experiments, we confirm that this TIW activity effectively damps regional cooling and exerts a negative feedback on the development of the subsequent La Niña event (Fig. 2). Quantitatively, on average in the Niño3 region, the 2024 TIWs reduced the amplitude of negative SST anomalies by 49%. The mixed layer heat budget further reveals that the total advection term dominates the SST warming (Fig. 3). In particular, its decomposed TIW-induced fluctuating component contributes a net heating of $0.81^{\circ}\text{C month}^{-1}$, which is around 2.8 times the net surface heat flux and one order of magnitude greater than background mean advection (Fig. 4).

Our results are consistent with previous studies highlighting the significant role of TIW-induced horizontal advection in cold tongue warming, arising from nonlinear interactions between ocean current and temperature (Jochum and Murtugudde 2006; Menkes et al. 2006; Xue et al. 2020; Wang et al. 2024). Specifically, TIWs create equatorward eddy heat flux that transport warm water toward the cold tongue via mixing across the SST front, causing heat flux convergence and mixed-layer warming (Baturin and Niiler 1997; Xue et al. 2021). It can better explain the intense TIW-induced warming band at 1°S – 4°N in boreal summer following the 2023/24 El Niño.

This study quantifies and demonstrates that TIW activity in 2024 contributed to the suppressed La Niña development. The strong TIWs during the decay of the 2023/24 El Niño counteracted the large-scale cooling driven by enhanced trade winds and upwelling, thereby weakening cold-tongue cooling. This mechanism complements existing explanations for the 2024 event, including westerly anomalies caused by off-equatorial warming (Shen and Zheng 2026) and wind-forced Kelvin waves (Tan et al. 2025). Furthermore, these findings, to some extent, support the theory of TIWs as an asymmetric negative

feedback on ENSO (Imada and Kimoto 2012; Holmes et al. 2019; Boucharel and Jin 2020). They highlight TIW-induced advection as a key thermal damping factor during ENSO transitions, which resonates with recent research by Xue et al. (2021) concerning anomalous TIWs hindering La Niña growth after the 2015/16 El Niño.

Nevertheless, it is essential to acknowledge several limitations in this study. The analysis performs the ocean-only model experiments and does not explicitly resolve TIW-induced air-sea coupling feedbacks, which could further modulate interannual variability associated with ENSO (Zhang and Busalacchi 2008; Zhang 2014). Moreover, this study only focuses on the heat budget within the mixed layer; thus, TIW-induced vertical components (i.e., advection and mixing) are not fully accounted for (e.g., Moum et al. 2009; Holmes and Thomas 2015; Cherian et al. 2021). Therefore, further studies should consider using coupled ocean–atmosphere models and multi-level heat budget analyses to examine TIW impacts on the tropical Pacific climate system.

Declarations

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Author Contribution

QC contributed to the initial draft and data analysis. RZ and HZ contributed to understanding and revising. LY and YL provided methodological guidance. All authors reviewed the manuscript.

Data Availability

The ECMWF ERA5 reanalysis is available at <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview>. The NOAA OISST is available at <https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html>. The CMEMS Global Ocean Physics Reanalysis (GLORYS12V1) dataset is available at <https://doi.org/10.48670/moi-00021>.

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Figures

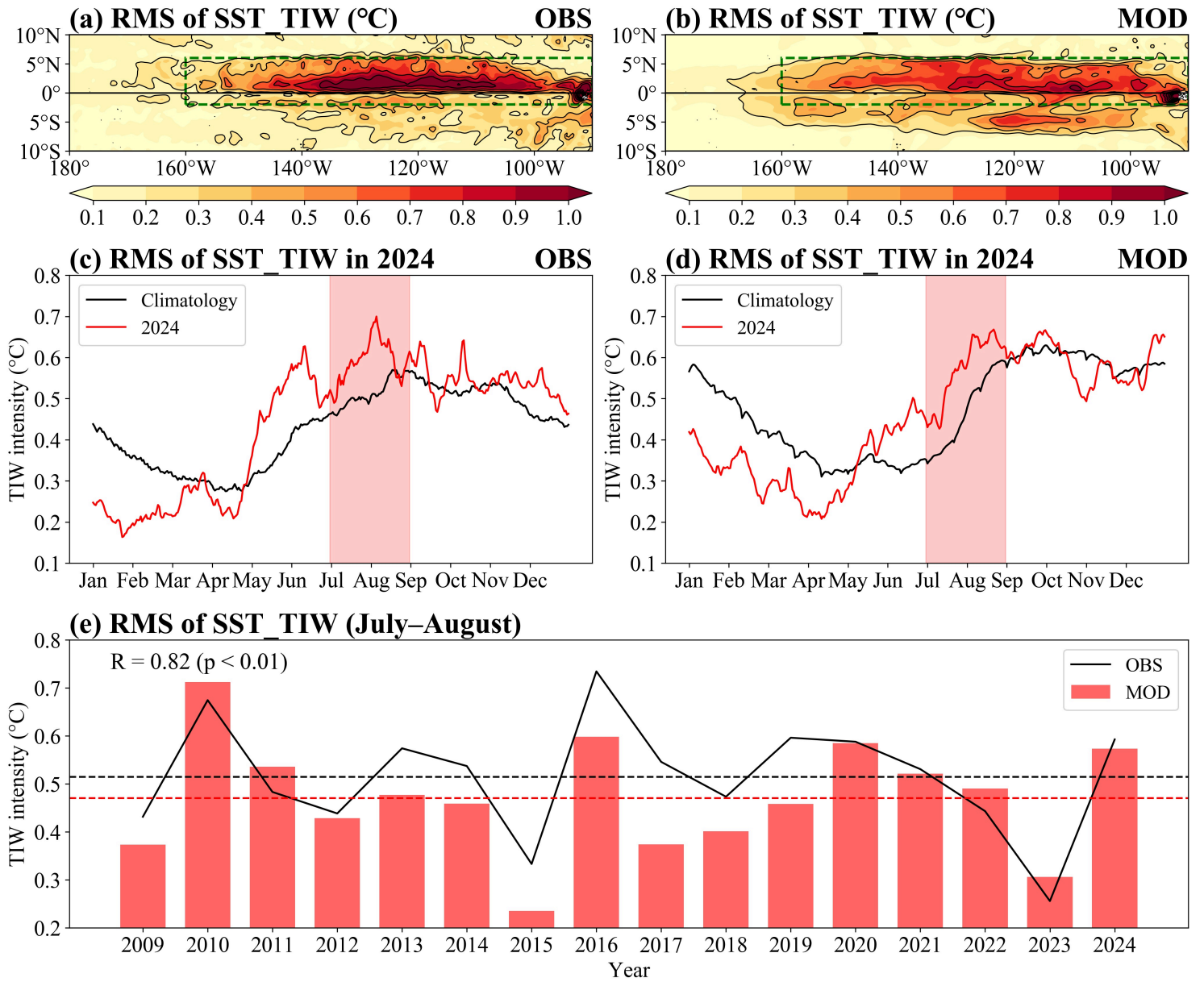


Figure 1

Horizontal distributions of root mean square (RMS) for TIW-induced sea surface temperature (SST_{TIW} , i.e., TIW intensity) calculated from daily (a) observed OISST and (b) simulated SST data in July–August of 2024. The contour interval is 0.2°C . (c, d) Observed and simulated time series of the TIW intensity for 2024 (red) and the climatology (black) over the TIW active region (2°S – 6°N , 160° – 90°W , green box in (a–b)). (e) Annual variability of observed (black solid line) and simulated (red bars) July–August TIW intensity during 2009–2024. The dashed lines represent their respective climatological means.

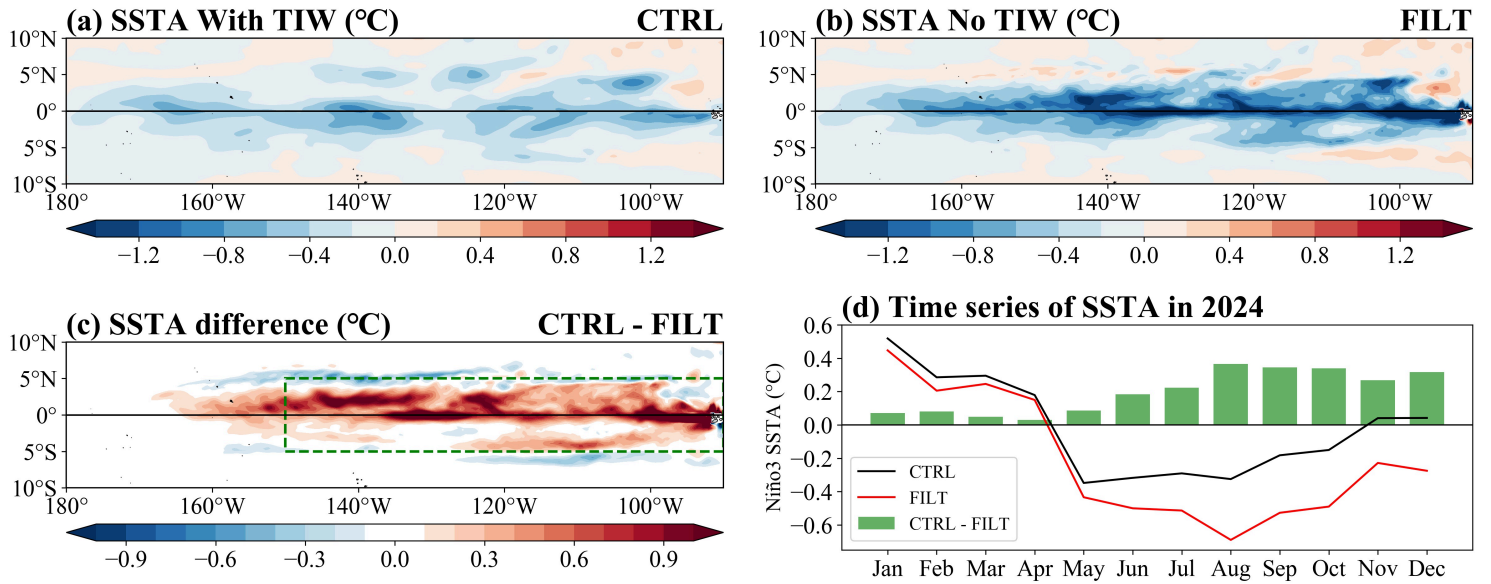


Figure 2

A comparison of the horizontal distributions for interannual SST anomalies (SSTA) in July–August 2024 simulated in (a) CTRL, (b) FILT, and (c) the SSTA difference between the CTRL and FILT. (d) Corresponding time series of CTRL (black line), FILT (red line), and their difference (green bars) for SSTA averaged over the Niño3 region (5°S–5°N, 150°–90°W, green box in (c)) in the year 2024.

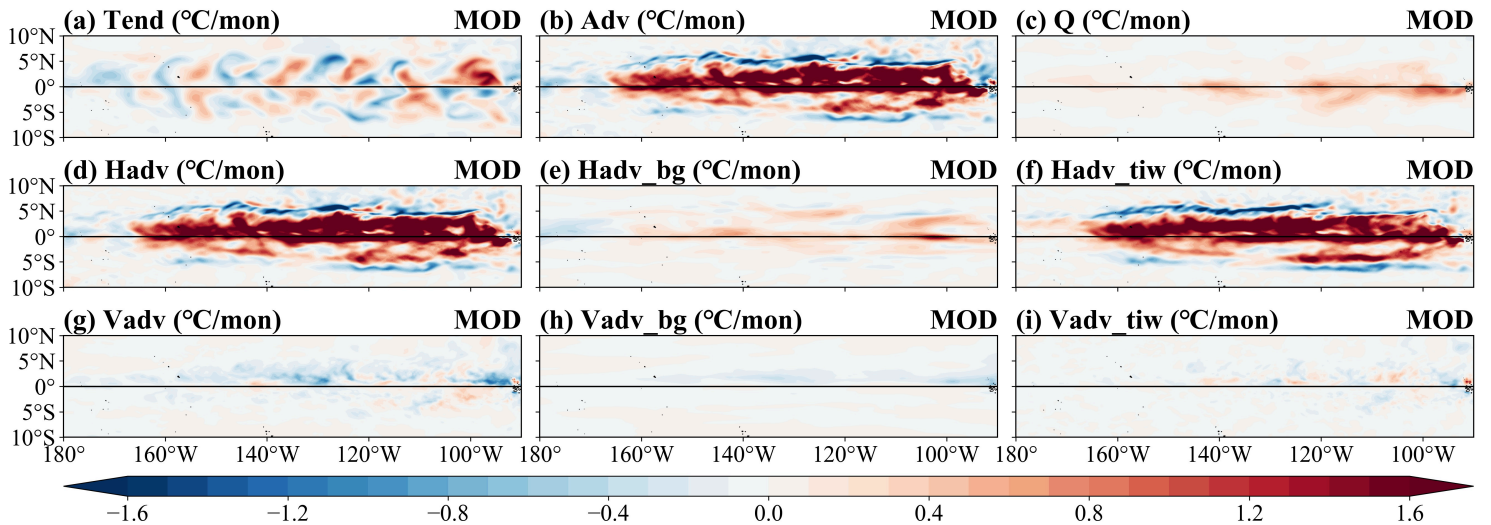


Figure 3

Horizontal distributions of the anomalous SST budget terms calculated from daily outputs of the OGCM simulations in July–August of 2024. Top three panels: (a) SSTA tendency (Tend), (b) heat advection (Adv), and (c) net heat flux (Q). Other panels show the (d)–(f) horizontal (Hadv) and (g)–(i) vertical (Vadv) components of the heat advection, decomposed into (left) total parts, (middle) background parts, and (right) TIW perturbation parts.

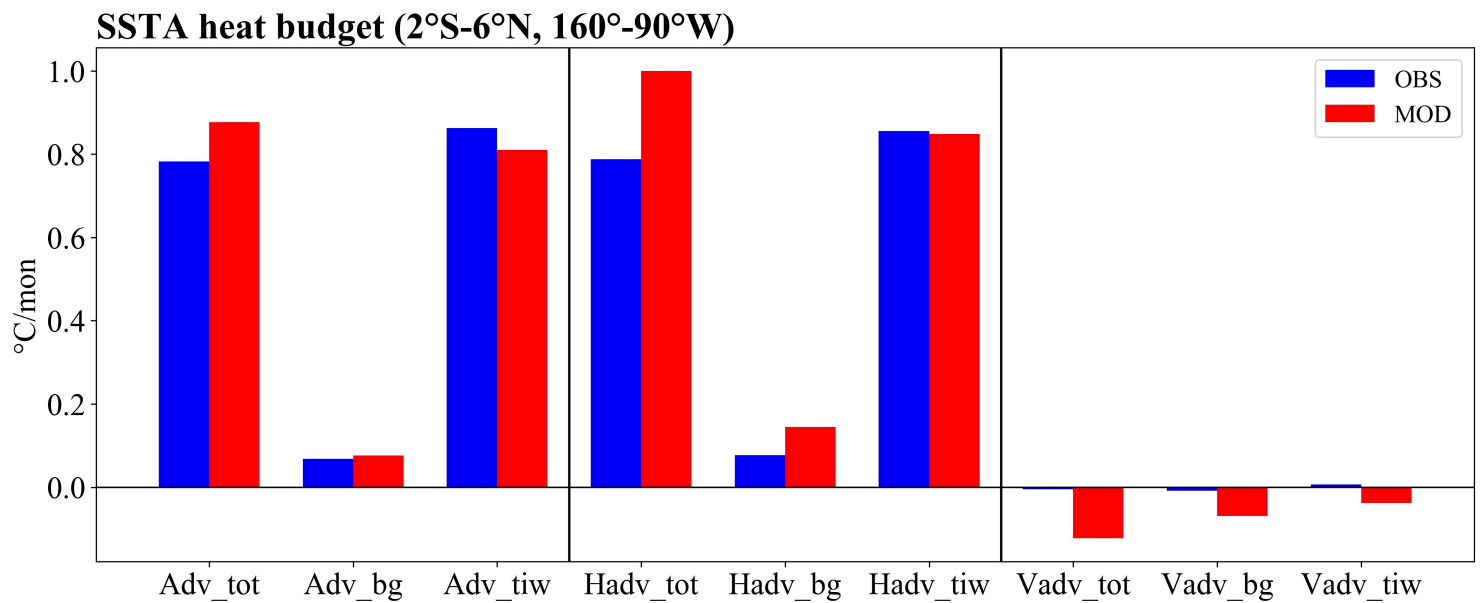


Figure 4

Comparison of the mixed layer anomalous SST budget terms averaged over the TIW active region (2°S–6°N, 160°–90°W) in July–August 2024 between observations (OBS, blue bars) and model simulations (MOD, red bars). The bars, from left to right, represent the total advection (Adv_tot), background mean advection (Adv_bg), and TIW-induced advection (Adv_tiw), as well as their respective horizontal (Hadv) and vertical (Vadv) components.

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